Input-Output Analysis (Subject Editor: Sangwon Suh)

A Method for Technology Selection Considering Environmental and Socio-Economic Impacts

Input-Output Optimization Model and its Application to Housing Policy

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Abstract

Goal, Scope and Background. In Japan, the abatement of CO_2 emission by households is a significant problem. Hence, it is necessary to formulate a long-term policy on the use of long-life and highly-insulating technologies for houses; these technologies are expected to reduce CO_2 emission. The conventional LCA methodology can evaluate the environmental impact of these technologies, while not necessarily providing sufficient information to support policy-making because of its analytical perspective. The aim of the present study is to first develop a new methodology to examine the optimal use of technologies to formulate an environmental policy by considering dynamic socio-economic conditions. Second, as a demonstration, such a developed methodology is applied to explore an environmentally conscious housing policy for CO_2 abatement in Japan.

Methods. A new methodology was developed, considering the context of a society where technologies are introduced, in order to determine the optimal configuration of technologies to minimize the cumulative environmental burden over time on a social scale. An inter-temporal linear programming model using an input-output table was formulated to make the methodology operational. Using the new model, the optimal use of long-life and thermal-insulating technologies for houses is examined to minimize CO_2 emissions across the entire life cycle of all the houses in Japan.

Results and Discussion. The results of the model simulation indicate that not only long-life and highly-insulating technologies, but also short-life and poorly-insulating technologies, are required to minimize CO_2 emissions over a long period. According to the conventional LCA, a house with a short life is inferior to that with a long life, and a house with poor insulation is inferior to that with high insulation. However, houses with a short life and/or poor insulation are introduced in a transition phase to a certain extent before the final stage is reached that is completely dominated by highly-insulated houses with a long life. In other words, the existing houses that were built in the past are gradually replaced with highly-insulated houses with a long life after first building houses with a short life and/or poor insulation. It is not always feasible or not necessarily an optimal solution on a social scale to introduce only a technology that is best evaluated by using the conventional LCA. Inferior technologies can also play a significant role because of various socio-economic conditions and requirements, e.g. population decline, limited housing budgets, and employment stability. Dynamic socio-economic conditions significantly influence the optimal mix of technologies for CO_2 minimization in the entire society.

Conclusions and Recommendations. The present study suggests that it is critical to consider dynamic socio-economic conditions when examining technologies for selection with the aim of a long-term reduction of the environmental burden. The new methodology proposed can provide valuable information to support policy-making toward a sustainable society.

Keywords: Dynamic; global warming; house; input-output table; life cycle assessment (LCA); linear programming; long-life house; optimization; policy-making; technology assessment; thermal insulation

1 Introduction

1.1 Background

With increasing concern over anthropogenic climate change, greenhouse gas emission due to human activities must be reduced. CO_2 emission from households continues to increase in Japan, and the reduction of CO_2 emission due to household activities is a significant problem. Improvement in the efficiencies of home appliances is an effective measure; further, improvement in the environmental performance of the houses, e.g. building a well-insulated and long-life house, is also an essential and fundamental requirement for the abatement of CO_2 emission. For example, if the house was well insulated, air conditioners with a high efficiency could contribute more to the reduction of CO_2 emission. The introduction of highly-insulating technology could considerably reduce CO_2 emission associated with heating, which accounts for nearly a quarter of the total emission from energy used in a household [1]. In addition, using long-life technologies could assist in achieving a substantial reduction in CO_2 emission from houses in the construction stage. The use of highly-insulating and long-life technologies is the key to the abatement of CO_2 emission from households in the future. Examining the application of these technologies in houses based on a long-term strategy is significant. This is because houses have a longer life than products that we use in our daily lives – televisions, air-conditioners, cars, etc.

1.2 Beyond the conventional LCA

Thus far, a life cycle assessment (LCA), particularly life-cycle CO_2 emission analysis, has been performed to evaluate

the effect of long-life and highly-insulating technologies from the perspective of climate change (e.g. [2–3]). From the previous LCA studies, CO_2 emission during the construction of a highly-insulated house with a long life (LH house) is greater than that of a poorly-insulated house with a short life (SP house) However, an LH house allows for substantial reduction in CO_2 emission during the usage stage due to energy savings in heating. From the viewpoint of the life-cycle CO_2 emission factor (t-CO_2/m^2/a), an LH house is superior to an SP house. The results of the conventional LCA suggest that the introduction of long-life and highly-insulating technologies should be promoted to mitigate climate change.

However, does the introduction of only these technologies really minimize the total CO_2 emission in an entire society? Although the conventional LCA provides valuable information to some extent, it fails to provide some critical information required for designing an environmentally conscious housing policy. The decision-making with regard to the introduction of these technologies must consider the following: the amount of CO_2 emission that can be completely reduced in a society by their introduction, the timing and scale of their introduction in order to minimize the total long-term CO_2 emission, any unpleasant side effect with regard to the socio-economic aspects due to the introduction of these technologies, etc. Unfortunately, the conventional LCA is unable to answer the above questions sufficiently due to their methodological characteristics, which are as follows: 1) deals only with the environmental aspects, 2) ignores temporal information, and 3) defines a functional unit at the product level. Concrete policy-making on environmental problems often demands that a socio-economic situation is considered; this is because environmental policy is linked to other social issues (e.g. housing policy and labor policy) and restricted by socioeconomic conditions. In addition, time is frequently a critical parameter, and an entire society, rather than a single product, is likely to be the suitable unit of analysis. When assessing the long-life and highly-insulating technologies, the reality of the society where these technologies are to be introduced must be considered more. For instance, the population of a society might increase or decrease in the future; many houses have already been constructed, and they cannot be immediately demolished or substituted; further, houses will be built depending on individual preferences and within limited budgets. These conditions are critical for formulating an environmental policy on houses. In general, in order to assess the environmental consequences of changes caused by a policy decision on technology/product selection, influences of dynamic socio-economic conditions on the decision must be considered. Since the conventional LCA cannot treat the reality in an appropriate degree of detail, it is necessary to develop a novel superior methodology to achieve this.

Some methodologies and models have been proposed that focus on the above-mentioned methodological characteristics of conventional LCA. Some studies address not only environmental but also social-economic aspects from the life cycle perspective [4–5]. For example, the impact of recycling technologies is evaluated using an economic input-output table with regard to not only CO_2 and solid waste emissions, but also employment and industrial output [4]. Furthermore, there have been some attempts to integrate the economic and environmental aspects; for example, the monetary valuation of environmental externalities across the entire life cycle of a technology/product [5]. These studies address the impact of a technology/product from both environmental and socio-economic viewpoints, while not considering temporal information sufficiently.

On the other hand, other studies exist that successfully deal with temporal information to assess the environmental impact of a technology/product [6–7]. For example, in order to address the issue of an automobile-replacement policy, the determination of optimal lifetimes of cars based on environmental criteria have been explored using optimization theory [6]. Moreover, besides introducing time as a parameter, some studies suggest the calculation of the environmental burden of all the products in a society rather than a single product [8–11]. For example, for formulating a building policy in the future, CO_2 emissions from all the buildings in Japan over a period of time are analyzed from the life cycle perspective [7]. These studies introduce time as a critical parameter and employ all the products in a society as a proper unit of analysis to assess the environmental impacts of a technology/product, while not explicitly dealing with socio-economic aspects.

The decision-making with regard to the selection of a technology/product for addressing environmental issues often requires a methodology to explicitly and simultaneously deal with three points that are usually ignored by the conventional LCA: 1) consideration of socio-economic aspects, 2) introduction of time as a parameter, and 3) treatment of the impact on a social scale.

Along with the above-mentioned development of methodologies and models, there has been a more comprehensive discussion on the attributional and consequential LCA [12–16] within the field of LCA. Such a discussion is essential to develop a methodology that can appropriately support decision-making. According to [12], "the attributional approach to LCI serves to allocate or attribute to each product being produced in the economy at a given point in time, portions of the total pollution (and resource consumption flows) occurring from the economy as it is a given point in time; the consequential approach to LCI attempts to estimate how flows to and from the environment will change as a result of different potential decisions". The approach that is to be used depends heavily on the question to be solved. It is likely that the consequential approach is suitable for analyzing the future environmental consequences caused by a social decision on technology/product selection. In other words, the question addressed by the present study, i.e. the choice of house-related technologies in the future, is considered to be the consequential approach-type. However, it is likely that the consequential LCA methodology has not been fully developed, although it has been the subject of much discussion. Thus, it is important to carry out further LCA studies and accumulate knowledge with respect to theories, operational models, and empirical analyses.

1.3 Aim and content of the paper

The present study aims at first developing a new methodology and operational model to assess the optimum use of technologies from a life cycle perspective based on environmental criteria. The methodology reveals an optimal technology configuration to minimize environmental burden over time on a social scale under various socio-economic conditions. The methodology is described as a mathematical model, combining optimization with economic input-output theories. The use of input-output tables for LCA has so far been discussed in the LCA community. Previous studies used input-output tables to primarily tackle problems in drawing system boundaries in LCA [17–24]; however, the present study proposes a different application of input-output tables, methodologically, which has been seldom attempted in the LCA community. Second, the developed model is applied to explore a housing policy toward the CO_2 abatement in Japan. The optimal use of residential long-life and highly-insulating technologies in the future is examined to minimize CO_2 emissions across the entire life cycle of all the houses in Japan.

Section 2 explains the conceptual framework of the new methodology using an illustrative example. In Section 3, the methodology is applied to the question of selection of long-life and highly-insulating technologies for houses, where the mathematical formulation of the model to solve the question is described. Section 4 shows the simulation results obtained using the model, and then describes their implications. Finally, Section 5 presents some conclusions and discussion points derived from the present study.

2 Methodology

The authors developed a new methodology to explore the best policy on technology/product selection from environmental aspects, considering various socio-economic conditions. The methodology can provide the optimal technology configuration to minimize the cumulative environmental burden over time in the entire society under various socio-economic constraints. The conceptual framework of the methodology is shown in **Fig. 1**, where a question on the selection of house-related technologies based on CO_2 emission criteria is used as an illustrative example.

1) The reduction of CO_2 emission from a long-term perspective is one of the social objectives. A decision-maker is expected to formulate a long-term CO_2 reduction plan based on the information she/he possesses regarding house-related technologies. The methodology uses the linear programming (LP) technique[1] to obtain an optimal technology configuration in the future toward CO_2 abatement. The objective function is to minimize *cumulative* CO_2 emission related to all the houses in a society for a given time horizon. The use of the LP technique permits answering the questions of "when, how much, and what technology options (e.g. long life, highly-insulating) should be adopted in a society for the CO_2 minimization".
2) *Cumulative* CO_2 emission is defined as the sum of *total* CO_2 emission from all life cycle stages of all the houses for a period *t* over an entire time horizon (**Fig. 2**). The total CO_2 emission at each period is calculated using an economic input-output (I-O) table, based on the inventory data of goods and services required over the life

[1] A conventional LP model as well as the relationship between LP modeling and LCA are well explained in [25]. In the field of LCA, the LP technique has been primarily used for treating the problem of allocation in multiple-function systems (e.g. [26]). The present study applies the LP technique to solve a question of decision-making with regard to technology/production selection.

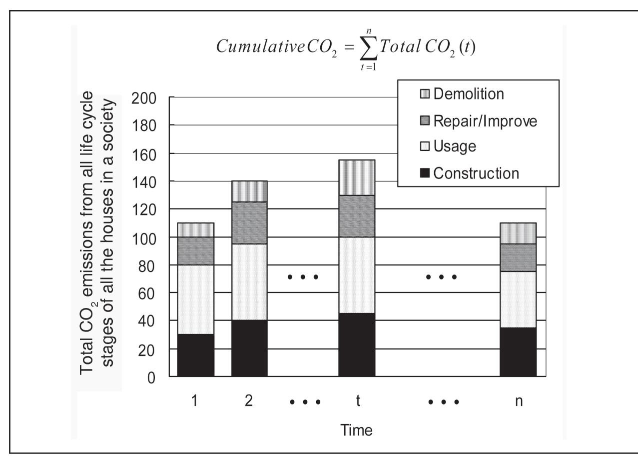

Fig. 2: Illustrative example of calculation of cumulative environmental burden

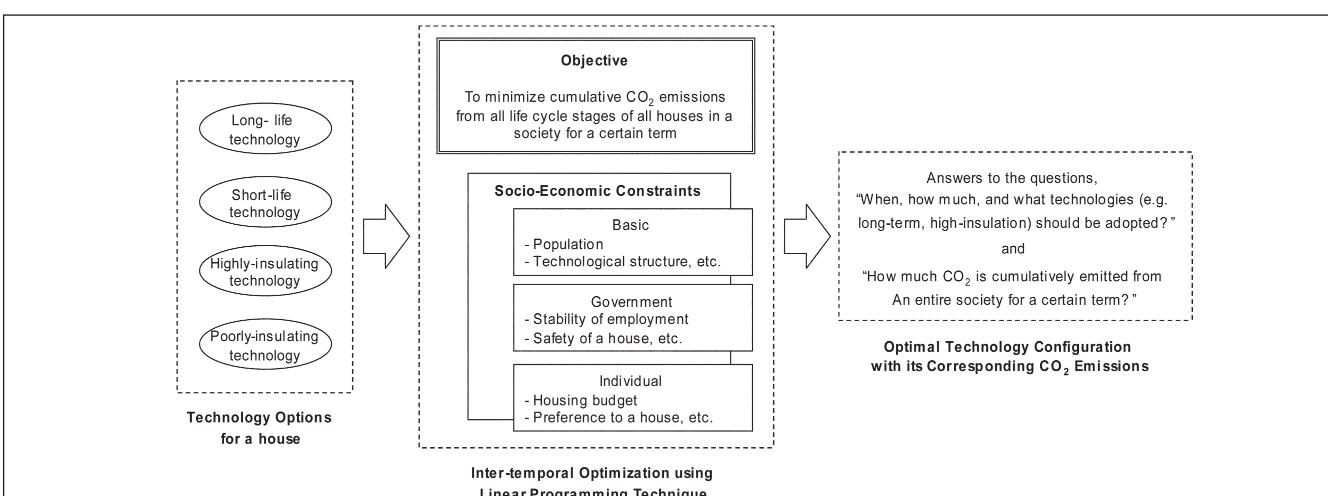

Fig. 1: Conceptual framework of a newly developed methodology

cycle of a house. The use of an I-O table allows for the consistent calculation of direct and indirect CO_2 emissions based on the technological structure of an economy.

3) When formulating a long-term CO_2 abatement plan, a government should simultaneously consider other social objectives, such as the building of safe houses, stability of employment, etc. Further, an individual maximizes her/his well-being based on her/his value systems under a limited budget, while they cooperate to some extent to achieve social objectives. In CO_2 minimization, such socio-economic conditions are described as constraints, which are classified into three types: 1) base, 2) government, and 3) individual. *Base constraints* represent inherent characteristics of a society, such as population and technological structure, which require relatively less government control. *Government constraints* are related to political issues such as stability of employment and the safety of houses against natural disasters, which a government has to simultaneously consider when formulating environmental policy. *Individual constraints* are based on the individuals' financial situation and value systems, such as life styles and preferences of houses.

In summation, the methodology assumes that when a government makes a decision on technology selection in the future, it will attempt to minimize the environmental burden of the criteria on a social scale over a long time period, considering various dynamic socio-economic conditions that affect the environmental consequences.

3 Applications of the Methodology

3.1 Options considered

The newly developed methodology was applied to explore an environmentally conscious housing policy. The present study focuses on the use of residential long-life and highly-insulating technologies[2] toward CO_2 reduction. The introduction of these technologies is classified into two cases: 1) they are applied when a house is newly constructed and 2) they are used for the improvement of an existing house.

[2] The present study deals only with detached houses, and apartments are not considered. Every house is assumed to be typical (e.g. floor area is 125 m²) in Japan according to [27].

In the present study, three different types of houses that will be newly built are considered, as shown in **Table 1**. These three types are characterized by differences in lifetime and insulation. The LH house uses long-life and highly-insulating technologies; in our study, as an example, it is assumed to be a steel house with exterior insulation. The LH house needs planned extensive renovation in 30 years after its construction. This renovation includes interior finishing that would make the house become suitable for meeting living conditions at that time, resulting in a social lifetime of 60 years. The SH and SP houses represent a short-life and highly-insulated house, and a short- life and poorly-insulated house, respectively. The lifetime of both the SH and SP houses are 30 years. The SH-house is assumed to adopt interior insulation using polyurethane. All the houses that were built in the past are assumed to be SP houses.

Long-life and highly-insulating technologies can be also applied later, after a house is newly built. As shown in **Table 2**, life-extending repair allows for extension of a lifetime by 10 more years for three different types of houses. For example, the lifetime of the LH house can be extended to 70 years. Repair can prolong the physical lifetime while not allowing for the extension of the social lifetime. Moreover, improvement in the insulation of an SP house is also considered. The insulation of an SP house can be improved during its lifetime by using sidings on its external walls.

3.2 Formulation of optimization model

An inter-temporal linear programming (LP) model with an input-output table was formulated to assess long-life and highly-insulating technologies based on the CO_2 emission criteria [28]. The GAMS (General Algebraic Modeling System) code was used to execute the LP model.

3.2.1 Objective function

It is assumed that a decision-maker attempts to minimize the sum of CO_2 emission associated with 'the production activities of all the goods and services in the entire society' caused by 'the demand for houses in the entire society'. The objective function is to minimize the cumulative CO_2 emitted from the life cycle stages of all the houses in Japan for 20 periods, as

Table 1: Three alternatives of newly built houses

	LH house	SH house	SP house
Characteristics	Long-life (60 years) Highly-insulated	Short-life (30 years) Highly-insulated	Short-life (30 years) Poorly-insulated
Main insulation materials	Polyurethane form (Exterior)	Polyurethane form (Interior)	Thin fiber glass (Interior)
Windows	Double glazing using Low-E glass	Double glazing using Low-E glass	Single Float glass
Price	Expensive	Medium	Inexpensive

Table 2: Life-extending repair and highly-insulating improvement

	LH house	SH house	SP house
Life-extending repair for 10 more years	Only once	Only once	Only once
Highly-insulating improvement during the lifespan	None	None	Only once

shown in **Eq. (1)**. In the model, a period is 5 years and the planning horizon is 20 periods (100 years, 1995–2094). E_t^C, E_t^U, E_t^R, and E_t^D in Eq. (1) denote CO_2 emissions associated with new construction, repair/improvement, use, and demolition of houses at period t, respectively. They are functions of a decision variable vector, $\mathbf{X}_t$, which is composed of elements representing floor areas of new construction, repair, and improvement in each type of house at t. $\mathbf{X}_t$ is decided to minimize the cumulative CO_2 emissions. The calculation of E_t^C, E_t^U, E_t^R, and E_t^D will be described in sub-section 3.3.

$$\begin{aligned}&Cumulative\,CO_2 = \\ &\sum_{t=1}^{20}\left(E_t^C(\mathbf{X}_t)+E_t^U(\mathbf{X}_t)+E_t^R(\mathbf{X}_t)+E_t^D(\mathbf{X}_t)\right)\rightarrow \min \quad t=1,2,\ldots,20\end{aligned} \tag{1}$$

3.2.2 Constraints

(1) Total floor area required in the future

The balance of the floor area at the end of each period is represented by **Eq. (2)**. S_t represents the total floor area existing at t; it is a function of the floor areas of each type of house newly built from period 1 to t and the floor areas of each house repaired from 1 to t. The total demand of floor area at t in the future, $Space_t$, was estimated mainly from population prediction and floor area required per capita (**Fig. 3**) [8,29–31].

$$S_t(\mathbf{X}_1,\mathbf{X}_2,\ldots,\mathbf{X}_t)\geq Space_t\,,\quad t=1,2,\ldots,20 \tag{2}$$

(2) Demand-supply balance of all the goods and services in an entire economy

Eq. (3) shows that the total production, $\mathbf{P}_t$, is greater than the sum of an intermediate demand, $\mathbf{A}_t\mathbf{P}_t$, and final demand, $\mathbf{X'}_t$, for each good/service. The vector $\mathbf{P}_t$ comprises elements representing the amount of goods/services produced in an economy. The vector $\mathbf{X'}_t$ includes all elements comprising the decision variable vector $[\mathbf{X}_t]_i$, and the other remaining elements, except decision variables, are zero. Here, elements having a value of zero imply that final demands of goods/services except for houses are not considered in this study, as described in 3.2.1. T indicates transposition. $\mathbf{A}_t$ is a technological coefficient matrix based on the Japanese I-O table for 1995 [32]. House-related sectors of the original I-O table are disaggregated in greater detail. The disaggregation

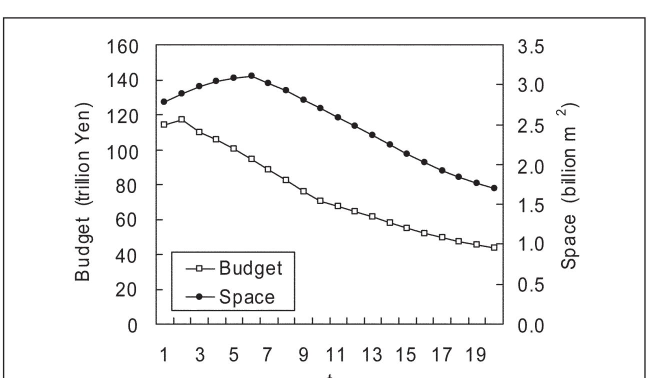

Fig. 3: The total demand of floor area and the total housing budget

was performed based on the good/service inventory for new construction, repair, and improvement of each type of house. The inventory data was obtained from house and material makers as well as official statistics [33]. The present study used a technological coefficient matrix for 1995 instead of that for the future, assuming that the technological structure in the economy does not change.

$$\mathbf{A}_t\cdot\mathbf{P}_t+\mathbf{X}'_t\leq\mathbf{P}_t\,,\quad t=1,2,\ldots,20 \tag{3}$$

where $\mathbf{X'}_t = (\mathbf{X}^T{}_t, 0,0,\ldots,0)^T$

(3) Stability of employment

Since stability of employment is crucial for a society, employment constraints were introduced as a government constraint. The rapid change in employment demand in an industry can lead to an increase in the unemployed in a society. This is because a certain amount of time is required to balance the employment demand in each industry with the number of people engaged in the industry. In particular, the construction industry requires more time to respond to the change in employment demand when compared with the manufacturing industry, because the construction industry relies more heavily on labor that has special techniques and skills [34]. Thus, in the present model, **Eq. (4)** was set to avoid an unstable employment demand in the house construction industry. Vector $\mathbf{J}_t$, representing the amount of jobs required for new construction, repair, and improvement of each type of house at t, was estimated from [32–33]. r_L and r_U indicate factors that restrict the change in the amount of jobs to some degree. In the base case, r_L and r_U were assumed to be 95% and 105%, respectively, based on the change in the number of people engaged in the house construction industry in the past [32,35].

$$r_L\cdot\mathbf{X}_{t-1}\cdot\mathbf{J}_{t-1}\leq\mathbf{X}_t\cdot\mathbf{J}_t\leq r_U\cdot\mathbf{X}_{t-1}\cdot\mathbf{J}_{t-1}\;t=1,2,\ldots,20 \tag{4}$$

(4) Total Housing Budget

Eq. (5) indicates that the construction and renovation of all the houses in Japan during a time period must be carried out within the total budget available for housing in the period. The total budget at t, $Budget_t$, represents the upper limit of money available for the overall construction and renovation at t in Japan. This study assumes that the total budget in a time period is equal to the sum of money that all people can pay for the construction and renovation of their houses in the period. $Budget_t$ was estimated based on a regression equation obtained from previous time-series data [31,36–38] and a future scenario (Fig. 3). The regression equation represents the relationship between the total budget and the values of independent variables, such as disposable incomes and population, in the past. The future scenario includes the values of their independent variables in the future. On the other hand, the cost vector $\mathbf{C}_t$, which represents the construction/renovation cost for each type of house, was estimated using data from house builders, etc., apart from official statistics [31,33,39–40].

$$\mathbf{X}_t\cdot\mathbf{C}_t\leq Budget_t,\;t=1,2,\ldots,20 \tag{5}$$

(5) Limitation of repair

Repair constraints were set as one of the individual constraints. Since life-extending repair cannot extend the social lifetime of a house, residents may not be able to endure a house that is not suitable for their lifestyle and preference. Setting repair constraints correspond to considering the quality of houses reflecting the preferences of the residents. Thus, **Eq. (6)** was set to restrain the total floor area of the repaired houses within a percentage, k_t, of the total demand of floor area, $Space_t$, at the end of each period. k_t was assumed to be 25% in the base case.

$$\sum_{i \in repair} X_{t,i} \leq k_t \cdot Space_t \ , \ t = 1,2,\ldots,20 \tag{6}$$

3.3 Calculation of total CO_2 emission

The present study focuses only on CO_2, and other greenhouse gases (e.g. CH_4, N_2O) are not included. CO_2 emissions from all life cycle stages – construction, usage, repair/improvement, and demolition – of all the houses in Japan are considered, as shown in Eq. (1).

3.3.1 Construction and repair/improvement

CO_2 emission associated with new construction at t, E_t^C, is estimated as in **Eq. (7)**:

$$E_t^C = \mathbf{e}^T (\mathbf{I} - \mathbf{A}_t)^{-1} \mathbf{X}'_t, \quad t = 1,2,\ldots,20, \tag{7}$$

where $\mathbf{X}_t$' is a demand vector including decision variables, and **e** is a vector consisting of direct CO_2 emission factors corresponding to sectors of $\mathbf{A}_t$ [41]. T indicates transposition. The use of an I-O table allows for a consistent estimation of not only direct but also indirect emissions from all industrial sectors. CO_2 emission for the repair and improvement, E_t^R, can be calculated as well.

3.3.2 Usage

Only CO_2 emissions associated with air-conditioning (i.e. heating and cooling) were considered in the usage stages. Lighting, home appliances, etc., were excluded because energy consumption, except for air conditioning, was assumed to be identical for all the houses.

Fig. 4 shows the estimation procedure of the energy required for heating and cooling for a certain floor area of a house for a year. The software 'SMASH'[3] was used for heat load estimation; it requires A) physical property data, such as floor area, room configuration, and heat characteristics of materials used, B) regional climate conditions, such as temperature, and C) operation-related data of an air conditioner (A/C), etc. The climate condition in Tokyo was assumed in the present study. It was assumed that electric air conditioners were used for heating and cooling, and kerosene stoves

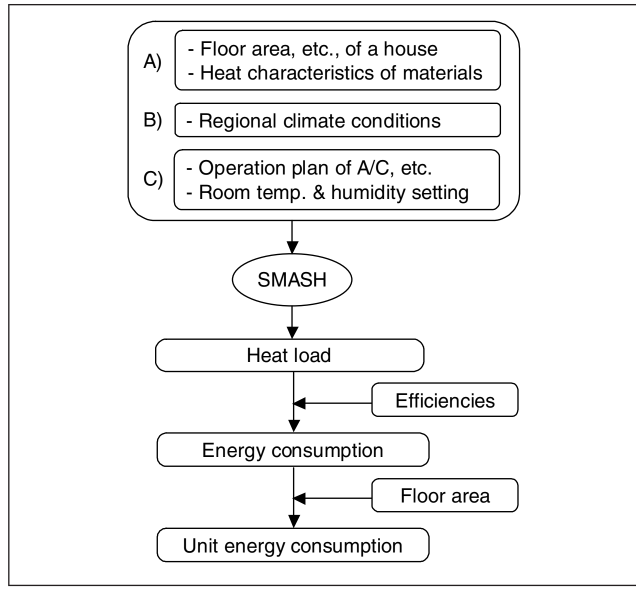

Fig. 4: Estimation of energy required for heating and cooling for a certain floor area of a house

were also used for heating. The operation plans of air conditioners, etc., and the temperature and humidity setting in the rooms were assumed to be typical for Japan according to [27]. After the heat load was estimated, the annual consumption of electricity and kerosene in a house was calculated using average COPs (Coefficient Of Performance) [42] of air conditioners and kerosene stoves used in Japan. Finally, the annual consumption of electricity and kerosene per floor area was estimated for the houses studied.

Based on the calculated unit energy consumption, CO_2 emission at the usage stage, E_t^U, is estimated in **Eq. (8)**:

$$E_t^U = \left(\mathbf{e}_t^T (\mathbf{I} - \mathbf{A}_t)^{-1} + \mathbf{F}\right)\mathbf{C}\,\mathbf{S}_t, \quad t = 1,2,\ldots,20 \tag{8}$$

E_t^U is a function of the floor areas of each house type existing at t, $\mathbf{S}_t$, depending on the floor areas of the houses built before period t. **C** is a matrix representing the calculated unit energy consumption for each type of house. **F** is the vector of direct CO_2 emission factors associated with the use of energy such as electricity and kerosene. Elements of **C** and **F**, except energy goods, are zero.

3.3.3 Demolition

CO_2 emission was estimated under the assumption that all combustible wastes (e.g. timber wastes) were burned and that materials were not recycled. CO_2 emission factors of combustible wastes and the cost of demolition were determined based on [43] and [44], respectively.

4 Simulation Results

4.1 Optimal technology configurations

Fig. 5 shows the result of the optimal solution for the base case, which is based on the optimization model presented in

[3] Simplified Analysis System for Housing Air-Conditioning Energy (SMASH) is a software developed by the Institute for Building Environment and Energy Conservation, Japan.

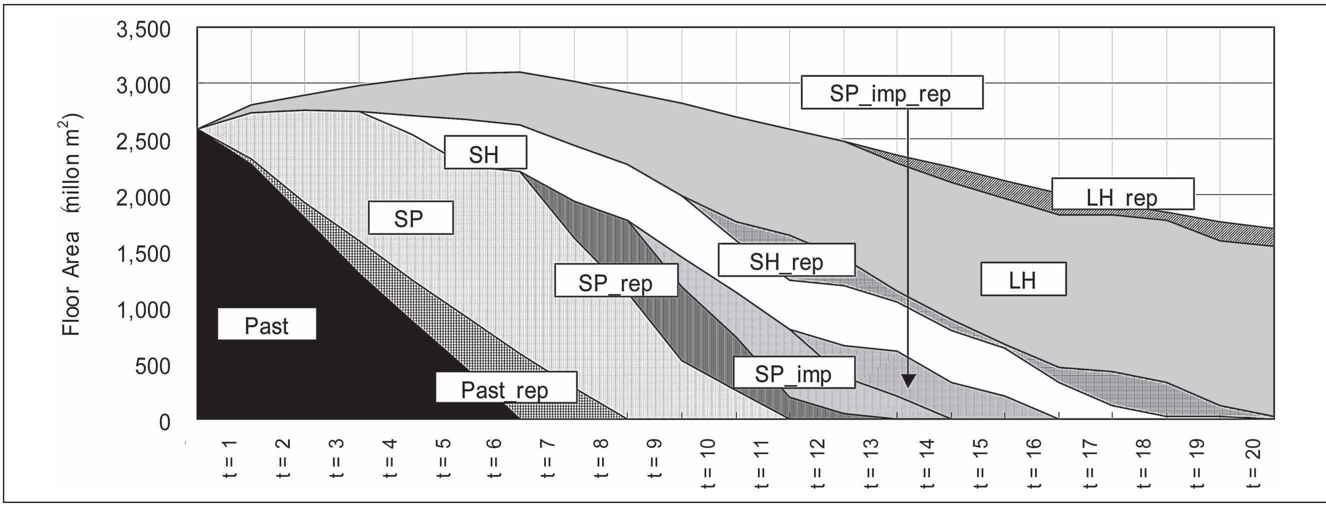

Fig. 5: The optimization result for the base case

sub-section 3.2. The x-axis represents time, while the y-axis indicates total floor area at a certain period t. The labels 'rep' and 'imp' represent repair and improvement, respectively. For example, 'SP_rep' indicates the SP house that was repaired for the life-extension; 'SP_imp_rep' denotes the SP house that was improved for better insulation during the lifetime and then repaired for the life extension. “Past” indicates the remaining houses that were neither improved nor repaired.

In order to meet the floor area demand in the future, 'Past' are either repaired or replaced by newly built houses, and additional houses are newly constructed. Conventional LCA results show that the life cycle CO_2 emission factor (t-CO_2/a/m²) for the LH house is the smallest among the three alternatives of newly built houses. However, according to Fig. 5, fewer LH houses than SP houses are expected to be constructed in the near future. For example, at $t = 3$ when nearly half of the houses built in the past are either replaced or repaired, the LH and SP houses account for 8% and 39% of total floor area, respectively. In the middle of the planning horizon, the proportion of the highly-insulated houses begins to increase. At $t = 13$, all the houses become the highly-insulated ones, while long-life houses still account for nearly half the total floor area. Finally, all the houses in the society become the LH house. In the base case, more SP houses are newly built as compared with LH and SH houses in the earlier period. This is primarily because the housing budget is constrained.

Fig. 6 indicates the optimization result for the case without housing budget constraints as shown in Eq. (5). In the no budget constraint (NBC) case, highly-insulated houses become dominant earlier as compared with the base case. Due to the abundant budget, almost all 'Past' are better insulated during their lifespan and all newly built houses are the highly-insulated houses (i.e. the SH or LH houses). As shown in Fig. 6, highly-insulated houses account for 100% at $t = 5$. On the other hand, long-life houses account for less than 20% of the total floor area at $t = 5$. Highly-insulated house diffuses faster in the NBC case than in the base case, while the diffusion patterns of the LH house until the middle of the planning horizon are similar for the two cases. It is noteworthy that, although the budget is not constrained, the floor area of the LH houses does not drastically increase as much

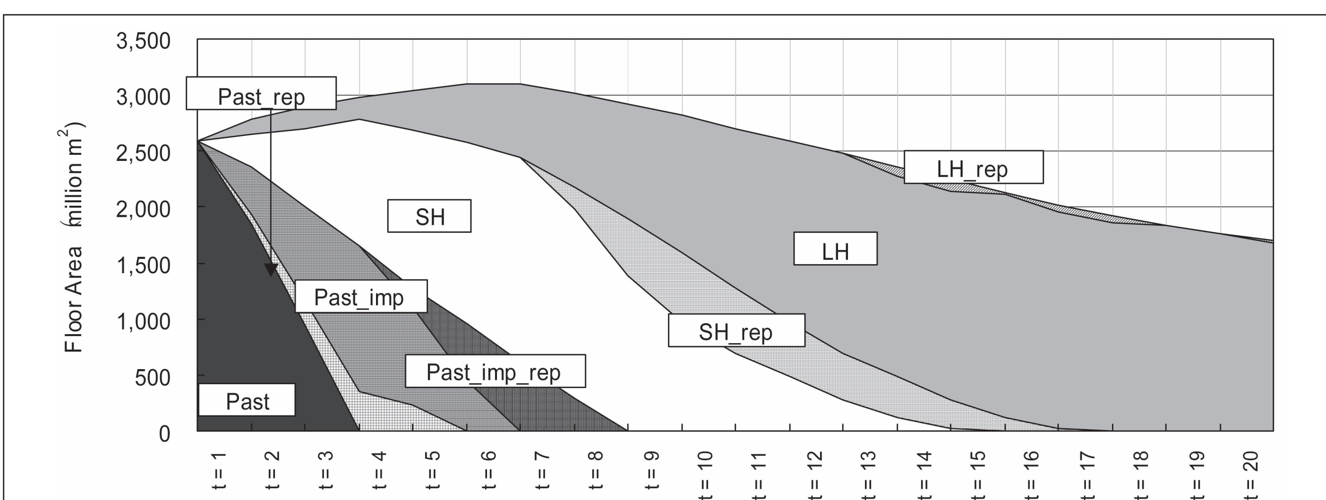

Fig. 6: The optimization result for the no budget constraint (NBC) case

in the near future. This is due to two constraints – the floor area demand starts decreasing from $t = 5$ because of a decline in the population, and the employment demand cannot rapidly change over a short term. The construction of more LH houses in the earlier period would generate a considerable surplus of houses (total floor area) from the middle period onward. Furthermore, this would subsequently lead to a rapid change of employment demand in the house construction industry. Thus, relatively more SH houses should be built in the earlier period to avoid increasing CO_2 emission associated with the construction of unnecessary houses and to maintain stable employment in the industry.

4.2 Cumulative CO_2 emission

Fig. 7 shows the change in CO_2 emission over time for two cases – the base and NBC cases. The cumulative CO_2 emission of the NBC case is nearly 7% less than that of the base case. The total CO_2 emission of the NBC case is smaller than that of the base case for almost all periods from $t = 1$ to $t = 20$. In the first half of the planning horizon, since the NBC case allows for a faster diffusion of highly-insulating technology due to the abundant housing budget, CO_2 emissions at the usage phase for the NBC case are considerably less than those for the base case. Although the application of highly-insulating technology increases CO_2 emission with regard to the new construction and improvement, the decrease in the usage phase exceeds the increase in the construction phase. In the second half, CO_2 emission in the usage phase for both cases are identical, while CO_2 emissions in the construction phase for the NBC case are lower than those for the base case. More long-life houses are newly built until the middle of the planning horizon for the NBC case as compared with the base case. As a result, the number of newly built houses is less in the later periods, and CO_2 emission associated with the construction is also less in the NBC case.

4.3 Technology selection on a social scale

The simulation results show that in order to minimize the cumulative CO_2 emissions, not only long-life and highly-insulating technologies, but also short-life and poorly-insulating technologies, are required. As shown in Fig. 5 and 6, the houses built in the past are not directly replaced with the LH house; instead, the replacement is gradual through SH and/or SP houses. The LH house, which is superior according to the results of the conventional LCA[4], accounts for 100% at the end stage in both the base and NBC cases. However, it is should be noted that although, according to the conventional LCA, short-life and poorly-insulating technologies are inferior, they need to be introduced to a certain extent to minimize the cumulative CO_2 emission on the social scale. It is dynamic socio-economic conditions that influence the optimal technology mix in the transition to the final status, which is completely dominated by the LH house.

Let us now consider an additional case, where only long-life and highly-insulating technologies are introduced (the OLH case). In the OLH case, every house built in the past becomes highly insulated during its lifetime; its life is extended by 10 more years, and every newly built house is the LH house. The cumulative CO_2 emission in the OLH case can be calculated using the results of the conventional $LCCO_2$ analysis if the floor area demand in the future is given. In the OLH case, socio-economic conditions, excluding the demand-supply balance of the floor area, are neglected. **Fig. 8** compares the cumulative CO_2 emissions for three different cases. The cu-

[4] Life-cycle CO_2 emission per m^2 per year (i.e. $LCCO_2$ emission factor) of the LH-house is the smallest among the three alternatives. In other words, the LH-house is best estimated with the conventional $LCCO_2$ analysis.

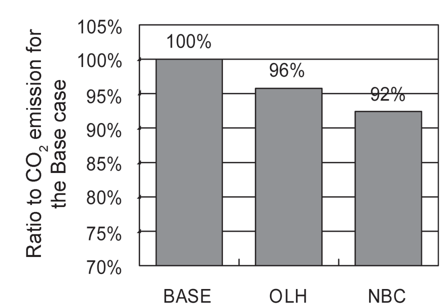

Fig. 8: Relative comparison of cumulative CO_2 emissions for three cases

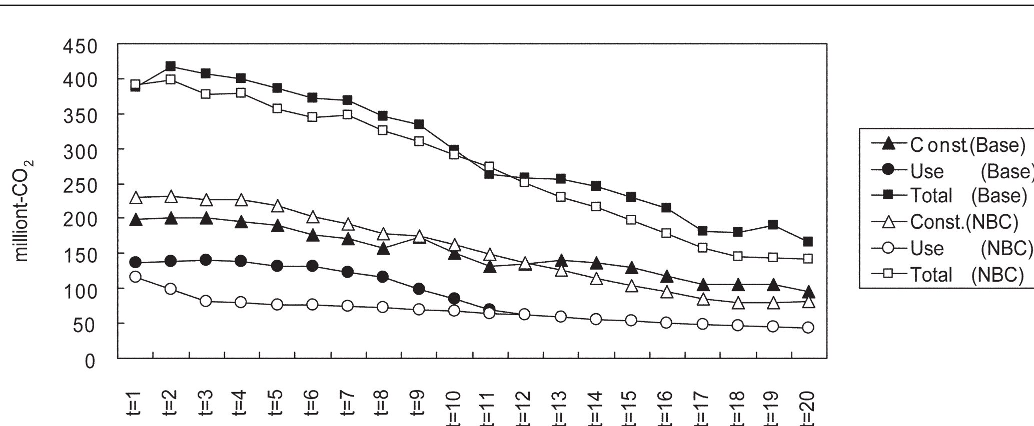

Fig. 7: CO_2 emission at each period for the base case and the case with no housing budget constraint (the NBC case). **Note:** Const. represents the sum of new construction, repair, and improvement

mulative CO_2 emission for the OLH case is less than that for the base case. It indicates that the complete introduction of long-life and highly-insulating technologies is infeasible if dynamic socio-economic conditions are considered. The OLH case is not feasible because both budget and employment constraints are violated. It is not always possible to use technologies that are best evaluated by conventional $LCCO_2$ analysis due to socio-economic conditions.

If socio-economic conditions change, the cumulative CO_2 emission also changes. The NBC case is the case where there are no constraints of housing budget due to sufficient subsidies, tax cuts, etc. The cumulative CO_2 emission for the NBC case is smaller compared with that for the OLH case. The CO_2 minimization in the NBC case requires the construction of houses with both a long and short life (see Fig. 6), while only the long-life house is introduced in the OLH case. Thus, in order to minimize the cumulative CO_2 emission under socio-economic conditions of the NBC case, the introduction of the short-life house, which is inferior according to the results of the conventional $LCCO_2$ analysis, is necessary along with the long-life house (see Fig. 6). In other words, CO_2 emission on a social scale does not always become minimum even if the technology is introduced that is the best estimated based on the functional unit.

The above results demonstrate that cumulative CO_2 emission on a social scale cannot be appropriately estimated from purely linear multiples of $LCCO_2$ emission factors. Such a calculation can lead to an underestimation or overestimation of CO_2 emission on a social scale. The conventional $LCCO_2$ analysis assesses which technology is superior or inferior based on a functional unit. Although such information is useful, real policy-making often requires information on the role that each technology can play to minimize CO_2 emissions on a social scale. In other words, it is required to find the optimal mix of technologies, i.e. when, how much, and what technology should be introduced based on the CO_2 emission criteria. The optimal mix depends heavily on dynamic socio-economic conditions.

5 Conclusions and Discussion

A methodology was developed to explore the optimal configuration of technologies to minimize environmental burdens on a social scale, by considering dynamic socioeconomic conditions. An inter-temporal optimization model with an input-output table was formulated based on the methodology, and the model was applied to technology selection for housing policy toward the long-term reduction of CO_2 emissions in Japan. The empirical study provided new knowledge and discussion points for the development of tools that support making environmental decisions.

5.1 The influences of dynamic socio-economic conditions

According to the empirical results, in order to minimize cumulative CO_2 emission associated with the overall demand of houses in Japan, not only long-life and highly-insulating technologies but also short-life and poorly-insulating technologies need to be introduced. Since it is assumed that the population in Japan will decease after it peaks in 2006 and the stability of employment are required to some extent, construction of short-life houses in the near future has an advantage. Moreover, poorly-insulated houses are adopted in the near future due to the upper limit of the housing budget. It should be emphasized that a decision with regard to the technology selection to mitigate environmental burden is not isolated from such dynamic socio-economic conditions. In other words, dynamic socio-economic conditions significantly influence a decision on when, how much, and what technology should be introduced to minimize environmental burden.

Due to dynamic socio-economic conditions, it is not always feasible or not necessarily optimal to introduce only a technology that is best evaluated with conventional LCA. It is likely that the minimization of environmental burden on a social scale requires the mix of two or more technologies including those that are inferior based on the conventional LCA results. This implies that the conventional LCA methodology may lead to potentially misleading results when examining the technology selection for the long-term reduction of environmental burden on a social scale. The conventional LCA methodology assesses which technology is superior or inferior based on a functional unit. Although such an assessment is useful information to some extent, real policy-making often requires information on the role that each technology can play to reduce the environmental burden on a social scale under various socio-economic conditions. The newly developed methodology can determine the optimal mix of technologies over time.

5.2 Modeling of reality and future uncertainties

The proposed new methodology, which allows for analyzing the relationships between the dynamic socio-economic conditions and environmental consequences, serves as a powerful tool for robust and effective environmental policy-making. However, the operational model still has scope for improvement, and the validity of assumptions in the future should be discussed.

The present results indicate that the housing budget is the most relevant for the minimization of a cumulative CO_2. Hence, more detailed modeling of a household's preferences and behavior is likely to be significant, e.g. the timing at which an individual builds a house, and the allocation of the housing budget depending on his/her preference, etc. Moreover, the present results also imply that the stability of employment would influence the technology selection and environmental consequences, which has received little attention so far. Thus, it may be worthwhile to explore the interaction between employment stability and technology selection more. This study deals with only the labor market for the house construction sector, although a macro-level unemployment rate may be more suitable as an indicator of social acceptability. Treating the unemployment rate in a society as a constraint requires consideration of labor movement between different industries, employment adjustment time for each industry, etc.

Since there are unavoidable uncertainties in the future, the simulation results in the present study also have various uncertainties. For example, the total housing budget was predicted based on both the results of regression analyses using time-series data and some assumed values (e.g. disposal incomes) with respect to the future. However, the future is not predictable, and these values are not necessarily valid for forecasting housing budget. Thus, the present study performed a simple sensitivity analysis on the extent to which the cumulative CO_2 emission in the future is influenced by the change in the housing budget. The result showed that a decrease of 1% in housing budgets for each time period increases the cumulative CO_2 emission by nearly 4%. Moreover, the employment constraint in the future may also change. This study sets the constraint based on the past data, although the constraint can or should be relaxed in the future. Apart from housing budgets and employment, technological improvements, changes in the technological structure in a society, and lifestyles, etc., also include future uncertainties. Therefore, in order to appropriately interpret the simulation results, uncertainties in the future should be correctly treated using either sensitivity or uncertain analyses [45–47], and forecasting methods that use scenarios [13,48]. More detailed modeling of the reality and the consideration of future uncertainties in important aspects could provide better information to support decision-making.

5.3 Implications for the consequential approach

This final sub-section describes two implications of the present study for the consequential approach. The first is about the importance of the transition phase that has been largely ignored by the LCA community. The consequential approach focuses on describing the consequences of changes caused by a decision or action. Not only the 'final consequences (result of changes)' but also the 'step-by-step consequences (process of changes)' can be valuable information for decision-makers. The developed methodology succeeds in revealing the process of changes by explicitly introducing the notion of time. First, the causal relationships between different times were modeled. An inter-temporal model is useful to analyze the step-by-step consequences by a decision with regard to technology/product selection in the future. Second, a basic scenario in the future (e.g. population, technological structure, households' disposal incomes) was adopted to simulate the state of technology selection using the model. In the empirical study, scenarios play a significant role, although the scenario development is not sufficient. In summation, the present study implies that the combination of inter-temporal modeling and scenario development in the future contributes to a prospective analysis on technology/product selection based on the consequential approach.

Secondly, it is important to include not only physical relationships but also socio-economic mechanisms in the studied system. The mechanisms or causal relationships that should be extracted from the real world are critical for the consequential LCA. The previous studies regarding system boundary selection using an economic input-output table (e.g. [23]) have shown that it is important to consider chains of causal relationships beyond the life cycle chain, by examining flows of goods in a whole economy. In addition, a recent discussion on the consequential approach (e.g. [13]) has indicated that it is also important to consider causal economic relationships such as the market mechanism along with physical (energy and materials) flows. However, the links between employment and the environmental consequences has been given little attention. Although the developed model does not still completely describe the mechanism related to employment as mentioned above, the present results imply that employment can hold an important key to foreseeing the environmental consequences. It is essential for the consequential approach to include factors and mechanisms that are influential in estimating the environmental consequences within the system studied. Thus, the manner by which influential factors and mechanisms are identified and extracted from all the causal relationships in the real world is important. The present methodology allows for exploring the factors/mechanisms that strongly affect the environmental consequences, by adopting an optimization model that represents various socio-economic factors as constraints.

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